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Faint galaxy counts as a function of morphological type in a hierarchical merger model

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ABSTRACT

The unprecedented resolution of the refurbished Wide Field and Planetary Camera 2 (WFPC2) on the Hubble Space Telescope (HST) has led to major advances in our understanding of galaxy formation. The high image quality in the Medium Deep Survey and Hubble Deep Field has made it possible, for the first time, to classify faint distant galaxies according to morphological type. These observations have revealed a large population of galaxies classed as irregulars or which show signs of recent merger activity. Their abundance rises steeply with apparent magnitude, providing a likely explanation for the large number of blue galaxies seen at faint magnitudes. We demonstrate that such a population arises naturally in a model in which structure forms hierarchically and which is dynamically dominated by cold dark matter. The number counts of irregular, spiral and elliptical galaxies as a function of magnitude seen in the HST data are well reproduced in this model.We present detailed predictions for the outcome of spectroscopic follow-up observations of the HST surveys. By measuring the redshift distributions of faint galaxies of different morphological types, these programmes will provide a test of the hierarchical galaxy formation paradigm and might distinguish between models with different cosmological parameters.

1 INTRODUCTION

Counting galaxies as a function of flux to very faint limits is one of the main tools for tracing the evolutionary history of the galaxy population. In combination with spectroscopic redshift measurements for brighter subsamples, this diagnostic has uncovered significant evolution in the galaxy population at moderate lookback times, corresponding to redshift $z \simeq 0.5$ (Lilly *et al.* 1995, Ellis *et al.* 1996). This raises the possibility that the onset of the process of galaxy formation itself may soon become accessible to observations.

The traditional approach to interpreting number counts is based on a retrospective calculation, in which the locally observed galaxy luminosity function and morphological mix are taken as the starting point. *Ad hoc* assumptions are then made regarding the time evolution of the luminosity and number density of galaxies and the epoch of galaxy formation. This approach is limited because it bypasses an explanation of the physical processes that drive galaxy evolution and lacks a clear link to current ideas on the formation of galaxies by the gravitational growth of primordial fluctuations.

A more satisfactory way to interpret faint galaxy data is to use the new methodology of semianalytic modelling of galaxy formation and evolution developed over the past five years (White & Frenk 1991, Lacey & Silk 1991, Cole 1991, Lacey *et al.* 1993, Kauffmann *et al.* 1993, Cole *et al.* 1994). In this approach, physically motivated models are constructed *ab initio*, starting from the power spectrum of primordial density fluctuations predicted by specific theories of structure formation. The current level of understanding of the dynamics of cooling gas, star formation, feedback of energy into prestellar gas and galaxy mergers is encoded into a few simple rules, often expressed in the form of scaling laws.

We describe the semianalytic model used in this paper in Section 2; for a detailed discussion of the technique, see Cole *et al.* (1994), and for an update of results see Frenk, Baugh and Cole (1996). The incorporation of morphological types into the model is described in full in Baugh, Cole, Frenk (1996). Our predicted counts are compared with HST observations in Section 3, along with predictions for the results of spectroscopic follow-up studies.

2 SEMIANALYTIC SCHEME FOR GALAXY FORMATION

In the Cole *et al* scheme, the hierarchical collapse and merging of an ensemble of dark matter halos is followed using Monte-Carlo techniques (Bond *et al.* 1991; Cole & Kaiser 1988). Gas associated with a halo virialises soon after halo collapse and then cools radiatively. Star formation procedes at a rate proportional to the mass of cold gas. The amount of gas that cools is, in turn, regulated by feedback associated with the effects of supernovae explosions and stellar winds. When a merger of dark matter halos occurs, the hot

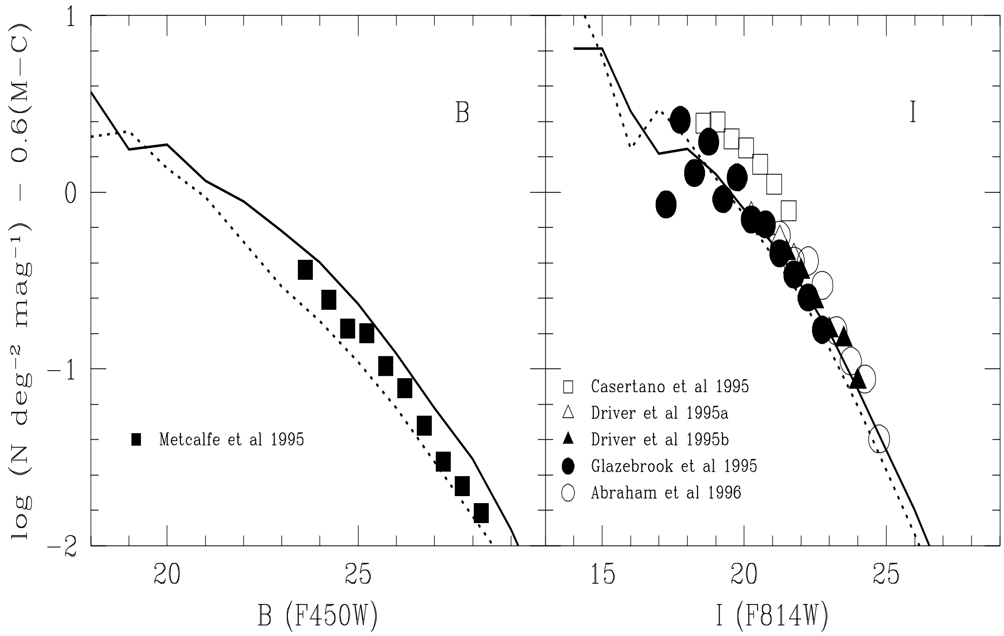

Figure 1. Number counts of galaxies of all types. The symbols show HST data in the B-band and I-band. The theoretical predictions are shown by the lines for two choices of IMF; the solid line shows a model with a Miller-Scalo IMF and the dotted line shows a model with a Scalo IMF. The counts have been divided by a power-law with the Euclidean slope of 0.6; the constant $C = 16$ for the B counts and $C = 14$ for the I counts. The pre-refurbishment Medium Deep Survey (MDS) counts (open squares) are higher than the WFPC2 counts by up to 50%.

gas of the progenitors is stripped away and assigned to the new halo. The cold gas and stars of the progenitors typically merge on a longer timescale than the halos. This timescale and other scaling parameters are calibrated by the results of numerical simulations (Navarro, Frenk & White 1993, 1995). The luminosities of the resulting galaxies are then calculated from their star formation histories using stellar population synthesis models (Bruzual & Charlot 1993; 1996 in preparation; Charlot, Worthey & Bressan 1996). A surprisingly small number of free parameters, five in all, is required to completely specify a model of galaxy formation within a given cosmology. Our general strategy is to fix the values of the free parameters by attempting to match properties of the *local* galaxy population as closely as possible. This results in fully specified models that can then be used to predict the properties of galaxies at high redshift. These models have been successful in recovering the general form of the galaxy luminosity function, the colours of galaxies and the counts and redshift distributions of faint galaxies in the B and K bands (Cole *et al.* 1994, Heyl *et al.* 1995, Frenk *et al.* 1996). However, a number of unresolved issues remain, most notably the inability of these models to simultaneously reproduce the observed local galaxy luminosity density and the zero-point of the Tully-Fisher relation (White & Frenk 1991; Kauffmann *et al.* 1993; Cole *et al.* 1994).

In this paper, we use an extension of the scheme of Cole *et al* in which the light of each galaxy is separated into a bulge and a disk component (Baugh, Cole & Frenk 1996). The normal mode of star formation occurs quiescently in a disk whilst the bulge component is assembled in galaxy mergers. Residual star formation in the bulge may occur if a sufficiently violent merger event triggers a burst of star formation. The bulge-to-disk ratio is thus a continually changing quantity and so the morphological type of a galaxy may change depending upon whether a merger has just occured or whether there has been a period of quiescent star formation. This schematic prescription is consistent with existing numerical simulations of galaxy mergers (Barnes & Hernquist 1992, Mihos & Hernquist 1994a,b) and with observations of luminous IRAS galaxies (Clements *et al.* 1996).

The ratio of the bulge-to-disk luminosity in the I-band, $(B/D)_I$, is used to assign a broad morphological type to the model galaxies: ellipticals have $(B/D)_I > 0.65$, SOs $0.40 < (B/D)_I < 0.65$, spirals $0.10 < (B/D)_I < 0.40$, and irregulars or late-type spirals $(B/D)_I < 0.10$. A galaxy that has experienced a violent merger within the 1Gyr prior to "observation" is classed as a "merger" with a disturbed morphology. These values of (B/D) and the threshold mass (in the form of cold gas and stars) that has to be accreted in a merger for it to be classed as violent are set by requiring that the local morphological mix of galaxies in the B-band be reproduced, within the uncertainties introduced by the subjectiveness of morphological classification. (Note that the observer-frame I-band corresponds to the rest-frame B-band at a redshift of $z \sim 0.8$.) As discussed by Baugh *et al.* (1996), this model produces a morphology-density relation and a small scatter in the colour of cluster ellipticals similar to those observed (Dressler 1980, Bower *et al.* 1992), and gives rise to "Butcher-Oemler" evolution in the morphological mix of cluster galaxies (Butcher & Oemler 1984).

In this paper, we use the fiducial parameters of the standard $\Omega = 1$ cold dark matter model of Cole *et al.* A

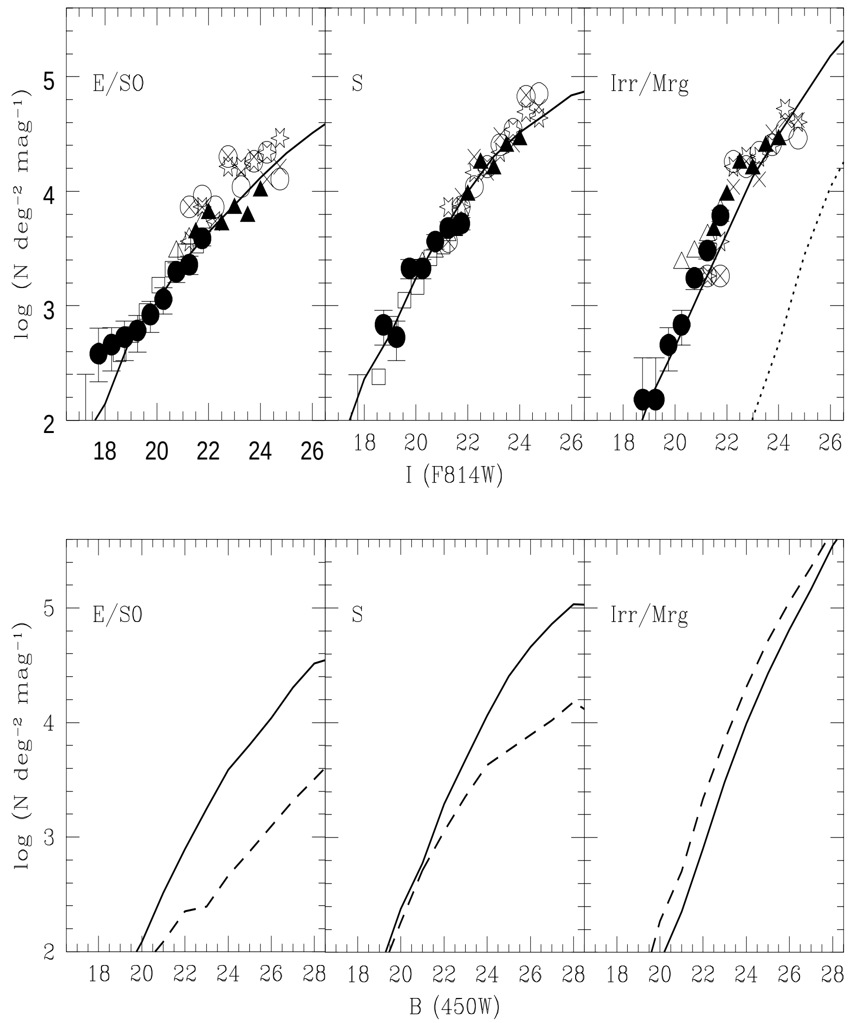

Figure 2. Number counts of galaxies of different morphological class. The upper panels show I-band counts and the lower panels B-band counts. The symbols represent I-band data from the same sources as in Figure 1, with the addition of crosses and stars to represent the counts classified by eye that supplement the automated counts in Abraham *et al.* (1996a). The lines show our theoretical predictions for a standard cold dark matter universe. The different morphological classes are defined in terms of the bulge-to-disk I-band luminosity ratio, as described in the text. The dotted line in the Irr/Mrg panel shows the contribution to the counts from objects that have undergone a major merger some time in the 1 Gyr prior to "observation". In the lower panels, the solid lines give the counts using the morphological assignment derived from the I-band bulge-to-disk ratio. The dashed line shows the counts when the galaxies are classified, instead, by their bulge-to-disk B-band luminosity ratio (using the same definitions of type employed in the I-band).

full discussion of the effect of varying these parameters or the underlying cosmology will be presented in a later paper (Baugh, Cole & Frenk in preparation). We set a dark matter halo mass resolution of $2 \times 10^9 h^{-1} M_\odot$ in our Monte-Carlo scheme. Galaxy magnitudes are computed using HST filters combined with the response of the optical system. From the output of our model we construct a mock Hubble Deep Field (HDF) catalogue, with magnitudes for each galaxy in the U(F300W), B(F450W), V(F606W) and I(F814W) bands.

3 MODEL PREDICTIONS

Figure 1 shows our predictions for the total counts in the B- and I-bands, compared to a compilation of HST results. We have divided the counts by a power-law of Euclidian slope, 0.6, in order to expand the ordinate. Our model predictions for the B-band counts depend somewhat on the assumed IMF. Our predicted counts for two plausible choices (the Scalo (1986) and the Miller-Scalo (Miller & Scalo 1979) IMFs) bracket the HST data. In what follows we shall adopt the Miller-Scalo IMF, but we note that the difference between the two sets of predictions are only slightly larger than corrections (~ 0.5 mag) required to zero-point the data. The I-band predictions, on the other hand, are very insensitive to the choice of IMF. The counts obtained from the pre-refurbishment HST (open squares) are clearly inconsistent with the WFPC2 data. Excluding these, our theoretical predictions are in excellent agreement with the data. The split of the counts into different morphological types is shown in Figure 2. The HST galaxies have been typed by eye by various groups (as indicated in the Figure caption) and by an

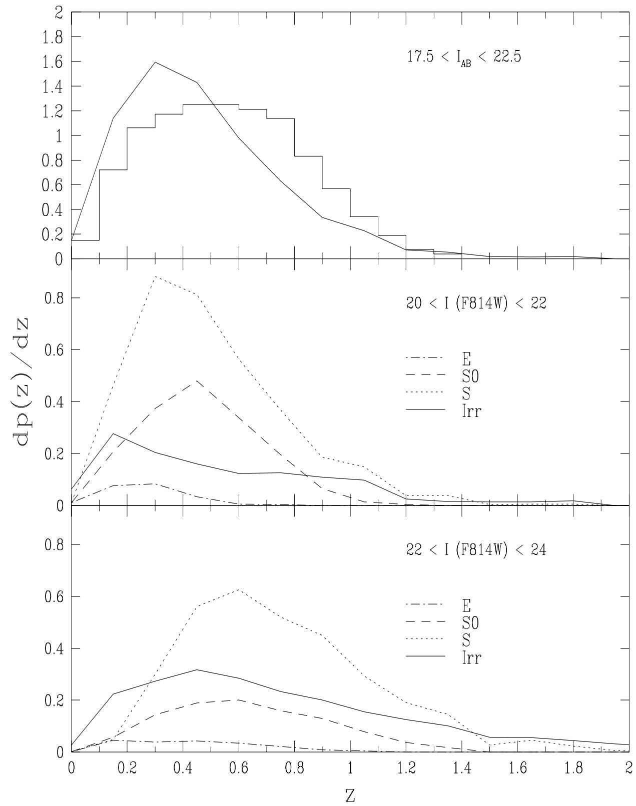

Figure 3. The redshift distribution of galaxy samples drawn from our mock HDF catalogue. The top panel shows galaxies selected with the same apparent magnitude limits as the Canada-France Redshift Survey data, which are represented by the histogram from Lilly *et al.* (1995). The central panel gives our theoretical predictions for galaxies of different morphological types and the same flux range as the sample selected for spectroscopic follow-up by Driver *et al* (1995b). The area under each curve gives the relative fraction of each galaxy type in the sample. The bottom panel shows predictions for a fainter magnitude slice that could in principle be observed with the Keck Telescope.

automated method that measures the asymmetry and central concentration of the image (Abraham *et al.* 1996a). In the top panels we compare these HST I-band data with our model predictions which extend 1.5 magnitudes fainter than the data. At the faintest observed fluxes, $I \simeq 25$, the spiral and irregular/merger classes contain comparable numbers, about a factor of 2 larger than the elliptical/SO class. Our model predicts that the counts of E/SO and S galaxies begin to turn over beyond $I \simeq 25$, but the counts of irregular/merger galaxies continue to rise steeply and dominates the I-band numbers faintwards of this limit. The main contribution to this class comes from galaxies with small bulges. Our model reproduces the observed trends remarkably well. By contrast, a retrospective model based upon the locally observed fraction of irregulars, a flat faint-end luminosity function and passive stellar evolution predicts far fewer irregular/merger galaxies than observed at these faint limits (Glazebrook *et al.* 1995).

The lower panels of Figure 2 give our model predictions for the counts in the B-band. The solid lines show the result of measuring B-magnitudes for galaxies classified as above, *ie* on the basis of their I-band bulge-to-disk ratio. Attempting to assign types using the observer B-band bulge-to-disk ratio leads to less reliable results (dashed lines in the bottom panel of Figure 2). This is because for redshifts $z > 0.5$, the observer B-band samples the rest-frame U and the far UV, and these are very sensitive to recent star formation. The observer I-band, on the other hand, gives a better measure of the mass in both the bulge and disk components. Mock CCD images of generic Hubble types, k-corrected to model their appearance at high redshift, demonstrate that ordinary galaxies can look very different in the rest-frame U and UV, becoming dominated by knots of HII emission in star forming regions which sometimes appear as chain-like structures (Cowie *et al.* 1996, Abraham *et al* 1996b).

In Figure 3 we plot our predictions for the redshift distribution of various subsamples drawn from our mock HDF catalogue. The top panel compares the model with the Canada-France Redshift Survey (Lilly *et al.* 1995). Overall, the agreement is very good, although the model produces approximately 20% too many galaxies at low redshift. This discrepancy reflects the steep slope of the local luminosity function ($\alpha \sim -1.5$) predicted in this (and similar) models, that has led to the claim that faint galaxies may be missing from local surveys, perhaps due to surface brightness effects (McGaugh 1994, Frenk *et al.* 1996). A detailed comparison of our model predictions with the CFRS measurement of evolution in the galaxy luminosity function out to $z \sim 1$ is given in Baugh *et al.* (1996). The middle panel shows our predicted redshift distributions for galaxies of different morphological types with $20 < I(F814W) < 22$, a choice that matches the limits of the sample of (Driver *et al.* 1995b) already selected for spectroscopic follow-up. We predict that spirals and SOs should have similar redshift distributions, with a median value of $z \simeq 0.45$ and a mean of $z \simeq 0.50$, whereas ellipticals should have a shallower distribution, with a median of $z \simeq 0.25$. The redshift distribution of irregular/merger galaxies peaks at an even lower redshift than this but it is very flat and has an extended tail beyond $z > 1$. The exact shape of this tail depends on the choice of IMF (Cole *et al.* 1994). Finally, the bottom panel gives our predictions for an even fainter magnitude slice which could, in principle, be measured with the Keck telescope. For galaxies with $22 < I < 24$, we predict a median redshift of $z_m \simeq 0.67$, increasing to $z_m \simeq 0.93$ for $24 < I < 26$. This increase in median redshift with decreasing flux contrasts with the behaviour of the 'maximal merger model' of Carlberg (1996), in which the median redshift remains around $z \simeq 0.6$ for galaxies fainter than $I = 20$.

The remarkable agreement between our theoretical predictions and the count data displayed in Figures 1 and 2 is not exclusive to the standard, flat CDM cosmogony. Equally good fits to the counts are obtained, for example, in an open CDM model with $\Omega = 0.3$ (Baugh, Cole & Frenk, in preparation). At high z, however, the redshift distributions do depend on the cosmological parameters. For this low-Ω model they have a similar shape to that of the standard model, but the peaks move by $\simeq 0.3$ to higher redshift. Thus, for the open $\Omega = 0.3$ cosmology, we predict median values of $z_m \simeq 0.91$ and $z_m \simeq 0.128$ for samples selected

with $22 < I < 24$ and $24 < I < 26$ respectively. Our predicted redshift distributions are in rough agreement with current observational data. Preliminary results by Koo *et al.* (1996) give a median redshift of $z \simeq 0.81$ for a sample fainter than $I = 22$. Cowie *et al.* (1995) find that 40 out of 281 objects identified as galaxies in a sample with $I < 22.5$ have measured redshifts $z > 1$. At this flux limit, our $\Omega = 1$ model has 7% of all galaxies lying at $z > 1$ and our open $\Omega = 0.3$ model has 2 to 3 times as many.

4 CONCLUSIONS

The simplest hierarchical clustering model – $\Omega = 1$ standard CDM – provides an acceptable theoretical framework for understanding the variation with flux of the relative numbers of galaxies of different morphological types seen in recent HST data. These data appear consistent with this extreme model in which galaxy formation occurs at relatively low redshifts (Frenk *et al.* 1985, Baugh *et al.* 1996). Number counts, however, provide only a limited picture of galaxy evolution and, within our class of models, they are compatible with a range of cosmological parameters. Essential complementary information is furnished by spectroscopic surveys to very faint limits such as those of Lilly *et al.* (1995) and Ellis *et al.* (1996). In an earlier paper (Baugh *et al.* 1996) we showed that, in broad terms, these data can also be successfully interpreted in the context of these models. Preliminary calculations (Baugh, Cole, Lacey & Frenk 1996 in preparation) suggest, further, that the existence of a population of "Lyman-break" galaxies at $z \simeq 3$, recently established by Steidel *et al.* (1996), may be compatible even with our standard $\Omega = 1$ cosmology. In this paper we have presented model predictions for spectroscopic follow-up programmes of the HST photometric surveys which offer the prospect of discriminating between different cosmologies. More generally, these and related high-redshift studies, will soon provide a definitive test of the idea that galaxies formed by the hierarchical aggregation of gravitationally unstable primordial fluctuations.

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